Constructed Wetlands: Efficiency, Economy, Power Savings Environmental Considerations and Design

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Chapter 1. Introduction

The use of constructed wetlands for wastewater treatment has increased dramatically over the past 30 years. This increase can be attributed to the versatility and the economic advantages of the systems, the recreational and educational benefits, wildlife habitats that provide birding, walking, etc., land preservation, erosion control and tourism. The systems can be designed for an exclusive commitment for the treatment of wastewater, advanced wastewater treatment, polishing of effluents from other processes, enhancement of wildlife habitat, public recreational activities or any combination of these. Coupled with this versatility are the economic advantages of the processes. In small communities where land is inexpensive and skilled labor is frequently limited, constructed wetlands provide an opportunity for the community to produce an excellent quality effluent at reasonable construction and operating costs. Even where land is expensive, when compared with the energy costs for conventional wastewater treatment processes, the lack of power consumption and the low operating cost will frequently offset the costs of the large land areas required for constructed wetlands.

Constructed wetland wastewater treatment processes are not limited to small communities. Design flow rates can range from less than 1,000 gallons per day (gpd) to over 20 million gallons per day (mgd). Design flow rates as high as 265 mgd have been proposed in Egypt. Constructed wetlands are used all over the world, and there are thousands around the globe.

Constructed wetlands come in a variety of shapes and forms and contain a variety of vegetation. Constructed wetlands are divided into two types: one with the water surface exposed to the atmosphere is referred to as a free water surface constructed wetland (FWS) and the other with the water surface below a rock bed is called a subsurface flow constructed wetland (SSF). A constructed wetlands wastewater treatment flow pattern (train) is shown in Figure 1:

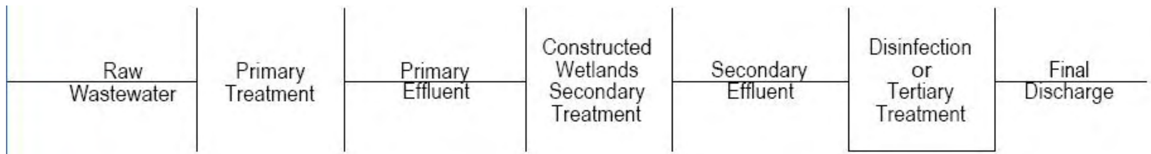


Figure 1. Constructed wetlands in wastewater treatment train (USEPA, 2000)

And the elements in a FWS constructed wetland are shown in Figure 2:

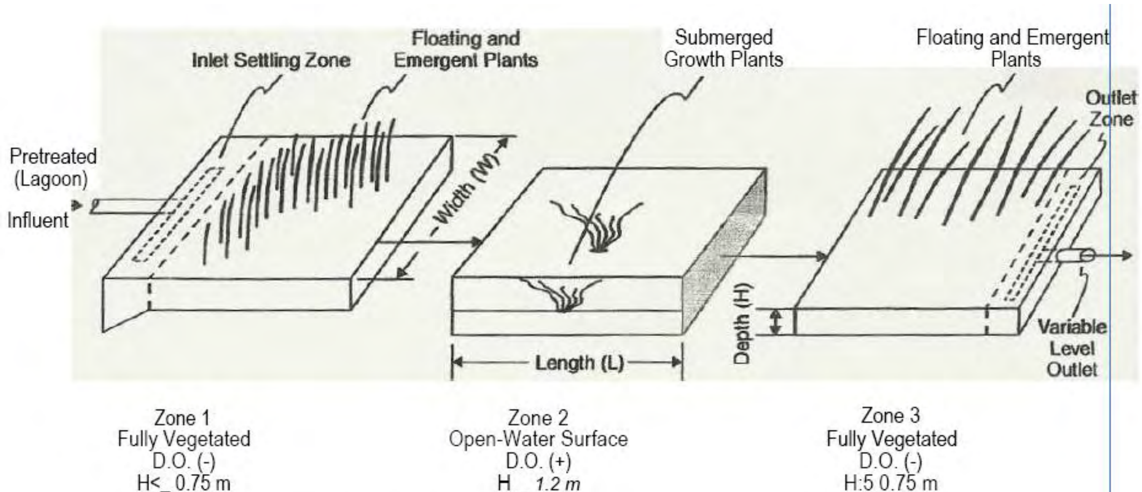


Figure 2. Elements of a free water surface (FWS) constructed wetland (USEPA, 2000)

FWS constructed wetlands contain most of the elements found in natural wetlands. Some FWS wetlands are fully vegetated while others are constructed with sizable sections of open water to aid in nitrification of ammonia-N. Subsurface wetlands are constructed with a gravel bed to support vegetation, and the water surface is below the gravel. The elements of a SSF constructed wetland are shown in Figure 3:

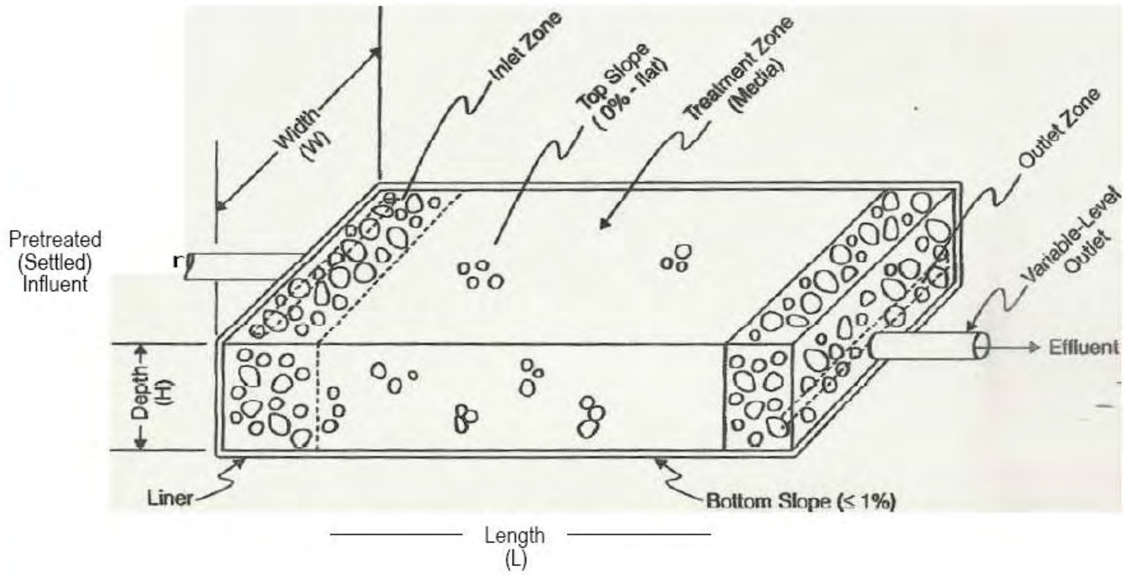


Figure 3. Elements of a subsurface flow constructed wetland (USEPA, 2000)

Detailed descriptions of both types can be found in Crites, Middlebrooks and Reed (2006), Colorado Governor's Office of Energy Management and Conservation (2001), USEPA (2000) and many other sources.

In this report the costs associated with constructed wetland wastewater treatment systems reported in the literature are summarized including construction costs, operating costs and energy savings. These costs are compared with the construction costs, operating costs and power consumption by mechanical treatment plants. Although there are thousands of constructed wetlands located throughout the world, there are a relatively limited number of sites where cost data are available. The costs reported herein are not exhaustive but include reliable data and represent a good cross-section of the savings that can be achieved by utilizing constructed wetlands.

Chapter 2. Energy Savings and Construction Costs

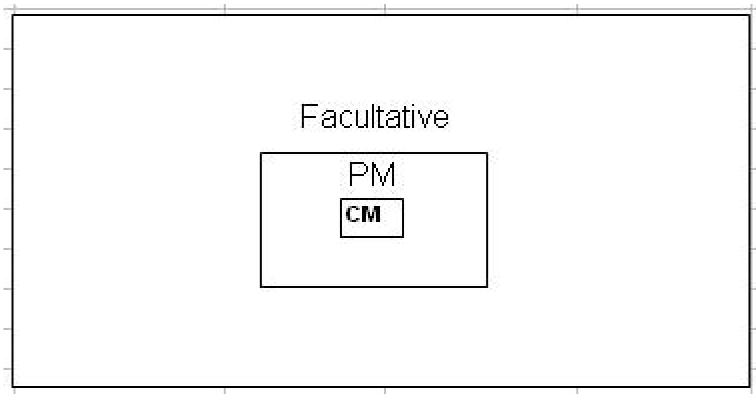
Pretreatment Processes

Wetlands are not recommended for use with raw wastewater; therefore, constructed wetlands are used in conjunction with some form of pretreatment. Pretreatment frequently consists of facultative lagoons that rely on natural processes for an oxygen supply or aerated lagoons that require mechanical aeration, and rarely, mechanical processes that consume significant quantities of energy. Lagoons can be designed as facultative with wind driven mixing and oxygen transfer, partial-mix that provides mixing adequate to transfer dissolved oxygen to the liquid, complete-mix that provides enough mixing to keep the solids in the system suspended and proprietary systems. In general, the proprietary systems can be described as variations of the facultative, partial-mix and complete-mix lagoons. The major differences in the types of lagoons are the methods of aeration, predominant organisms and the size of the systems.

Before selecting a pretreatment system, an economic analysis must be conducted that includes land, power, operation and maintenance, and construction costs. In small communities combinations of lagoons and constructed wetlands almost always will result in a competitive economic advantage.

Facultative Lagoons

In facultative lagoons the natural transfer of dissolved oxygen (DO) needed by the organisms to breakdown the organic matter in wastewater is transferred from the air to the water and the respiration of algae that grow in the lagoon. Mixing provided by wind action distributes the oxygen throughout the top few feet of the lagoon. As the name implies, there are facultative organisms as well as aerobes, and on or near the bottom of the lagoon anaerobic organisms breakdown the organic matter that settles to the bottom. Facultative organisms can function in the absence of molecular oxygen (DO). The relative size of a facultative lagoon treating 1 million gallons of wastewater per day (mgd) when compared to partial-mix and complete-mix lagoons is shown in Figure 4:



Design Assumptions

Air Temperature =	3	^{0}C
Influent Temperature - Winter =	10	^{0}C
Influent Temperature - Summer =	15	^{0}C
Influent BOD =	200	mg/L
Effluent BOD =	30	mg/L
Elevation =	1616	meters
Minimum Dissolved Oxygen in Lagoon =	2.5	mg/L

Type of Lagoon	Power Consumption kWh/yr	$/yr @ $0.07/kWhr	Hydraulic Res. Time days	WS Area ac	Depth ft
Facultative	0	0	54	166	9
Partial-Mix	410,320	$28,722	34	8	15
Complete-Mix	965,180	$67,562	5	1.5	15

Only total containment and controlled discharge lagoons are larger than facultative lagoons, and these are rarely used as pretreatment lagoons.

The major disadvantage of facultative lagoons is the semiannual “turnover” of the contents of the lagoon. This can result in significant odor problems if the facility is located near or up-wind of the community. By proper location, this disadvantage can be overcome.

Partial-Mix Lagoons

Dissolved oxygen is provided by mechanical means in a partial-mix lagoon, and this frequently is the only component of a lagoon-wetland system requiring energy input. The partial-mix lagoon is sometimes referred to as a facultative aerated lagoon.

This is because the mechanical aeration only partially mixes the lagoon and supplies the oxygen required for aerobic conditions in a portion of the lagoon. Solids settle and also are decomposed by anaerobes on the bottom of the lagoon as in the facultative lagoon. Mechanical aeration is needed because the size of the system is much smaller than a facultative lagoon (Figure 4), and adequate DO cannot be transferred from the air and the concentration of algae producing DO is inadequate because of the limited surface area.

Complete-Mix Lagoon

Complete-mix lagoons require far less land area than other types of lagoon systems (Figure 4). All of the solids in a complete-mix lagoon are kept suspended by aeration and relatively few algae grow in an aerated lagoon. By mixing the solids, the system approaches an activated sludge system without recycling the solids. The system is more efficient in terms of reducing BOD_5 (Biochemical Oxygen Demand, the dissolved oxygen used by microorganisms over a five-day period to oxidize organic matter), but the power input can offset the advantages of this type lagoon. Where land prices are prohibitive, utilizing the complete-mix lagoon can be financially competitive.

Energy Savings

Table 1 contains a list of the various combinations of treatment processes available along with the energy consumption per year and the quality of effluent expected. It is obvious that the energy savings associated with constructed wetlands and lagoon systems is exceptional.

Table 1. Total Annual Energy for Typical 1-mgd System Including Electrical and Fuel

Treatment System	**Effluent Quality mg/L**				**Energy**
	BOD	SS	P	N	(1000 kWh/yr)
Facultative Lagoon + Free Water Surface (FWS) Wetland	10	15	4	10	150
Facultative Lagoon + Subsurface (SSF) Flow Wetland	10	<10	7	10	150
Facultative Lagoon + Rapid infiltration	5	1	2	10	150
Facultative Lagoon + Slow rate, ridge + furrow Land Treatment)	1	1	0.1	3	181
Facultative Lagoon + Overland flow	5	5	5	3	226
Facultative lagoon + intermittent sand filter	15	15	-	10	241
Facultative lagoon + microscreens	30	30	-	15	281
Aerated lagoon + intermittent sand filter	15	15	-	20	506
Aerated lagoon + FWS Wetland	10	15	4	10	506
Aerated lagoon + SSF Wetland	10	<10	7	10	506
Extended aeration + sludge drying	20	20	-	-	683
Extended aeration + intermittent sand filter	15	15	-		708
Trickling filter + anaerobic digestion	30	30	-	-	783
RBC + anaerobic digestion	30	30	-	-	794
Trickling filter + gravity filtration	20	10		-	805
Trickling filter + N removal + filter	20	10	-	5	838
Activated sludge + anaerobic digestion	20	20	-	-	889
Activated sludge + anaerobic digestion +	15	10	-	-	911
filter	15	10	-	-	1051
Activated sludge + nitrification + filter					
Activated sludge + sludge incineration	20	20	-	-	1440
Activated sludge + AWT	<10	5	<1	<1	3809
Physical chemical advanced secondary	30	10	1	-	4464

Modified from Middlebrooks, et al. (1981)

The construction costs for facultative and aerated lagoons coupled with FWS constructed wetlands are summarized in Table 2 for systems located throughout the USA. :

Table 2. Construction Costs of Free Water Surface Wetlands
(Crites, Middlebrooks and Reed, 2006)

Location	Design Flow	Area	Construction Costs	Log Q	Log CC
	mgd	ac	$/ac		
			ENR-CCI = 5895		
<1 mgd					
Armour, SD	0.1	4	31091	-1	4.49263469
Baltic, SD	0.1	4	34227	-1	4.53436883
Cannon Beach, OR	0.68	16	49089	-0.16749	4.69098419
Eureka, SD	0.28	40	14500	-0.55284	4.161368
Ft. Washakie, WY	0.18	1.6	61827	-0.74473	4.79117817
Ft. Deposit, AL	0.24	14.8	32906	-0.61979	4.51727509
Mays Chapel, Maryland	0.04	0.6	64340	-1.39794	4.80848106
Mcintosh, Maryland	0.06	9.2	73650	-1.22185	4.86717275
Ouray, CO	0.36	2.2	53077	-0.4437	4.72490637
Tabor, SD	0.065	2	31768	-1.18709	4.50198987
Tripp, SD	0.075	4	29262	-1.12494	4.46630401
Vermontville, MI	0.1	11.4	116860	-1	5.06766588
Wakonda, SD	0.05	2	26024	-1.30103	4.41537405
Average <1 mgd			47586		
>1 mgd					
Show Low, AZ	1.4	201	1996		
Lakeside, AZ	1	127	4425		
Hayward, CA	9.7	172	5828		
Lakeland, FL	14.8	1400	6970		
Mandan, ND	1.5	41	8155		
West Jackson Co., MS	2.4	50	14037		
Carolina Bay, SC	2.5	702	14465		
Incline Village, NV	3	428	16604		
Minot, ND	5.5	34	17635		
Arcata, CA	2.3	38.5	18830		
American Crystal Sugar, ND	1.5	81	24443		
Ironbridge, FL	20	1220	25165		
Mt. Angel, OR	2	10	39572		
Gustine, CA	1	24	51032		
Average >1 mgd			17797		

Subsurface wetland data for various locations are presented in Table 3:

Table 3. Construction Costs for Subsurface Flow Constructed Wetlands
(Crites, Middlebrooks and Reed, 2006)

Location	Design Flow	Area	Construction Cost	Gravel	Gravel	Quantity of	Cost	1997 Cost
	gal/day	acres	$/acre	Size	Depth	Gravel	$/yd^3	of Gravel
			ENR-CCI 5895	inches	ft	yd^3/ac		$/ac
La Siesta, Hobbs, NM	5000	0.11	198,900					
Howe, IN	6000	0.14	221,700					
McNeil, AR	15,000	0.39	263,300					
Santa Fe Opera, NM	17,000	0.15	374,000					
Phillips H. S. Bear Creek, AL	20,000	0.5	94,600					
Carville, LA	100,000	0.57	234,700	3/4 top layer	0.5	806	20.75	18,103
				1/2 to 3 bed	2	3226	15.45	53,952
Benton, LA	310,000	1.19	294,100					
Mesquite, NV	400,000	4.8	130,800	3/8 to 1	2.67	4308	8.4	43,800
Carlisle, AR	860,000	1.09	379,500					
Ten Stone, Vermont				3/8 top layer	0.5	806	19.17	15,451
				3/4 to 1 bed	2	3226	9.18	29,615

Similar cost data for FWS and SSF wetlands located in Iowa are shown in Table 4:

Table 4. Construction Costs for Iowa Free Water Surface Flow and Subsurface Flow Constructed Wetlands
(Iowa Energy Center and Iowa Association of Municipal Utilities, 2001)

Location	Wetland Cost	Wetland Acres	Cost/Acre	Year
Surface Flow Systems Wetlands				
Agency	$30,000	3.5	$8,571	1994
Chelsea	$20,000	0.26	$76,923	1990
Dows	$53,201	2.3	$23,131	1991
Iowa City	*$25,000	0.55	$45,455	1998-99
			Avg. = $38,520	
			Range= $8,571	
			to $76,923	
Subsurface Flow Wetlands				
Lake Vista Motel	$23,000	0.88	$26,135	1997
Burr Oak	$38,000	0.24	$158,333	1993
IAMU	*$18,000	0.15	$120,000	1999
			Avg - $101,489	
			Range=$26,135	
			to $158,333	

All costs are estimated except when actual costs were available and are indicated with *.
These costs are to provide guidance only and don't reflect up-to-date costs.

Construction costs for Iowa treatment systems containing FWS and SSF constructed wetlands are presented in Table 5:

Table 5. Construction costs for treatment systems that include FWS flow and Subsurface Flow Constructed Wetland Systems
(Iowa Energy Center and Iowa Association of Municipal Utilities, 2001)

Systems	System Cost	Wetland Acres	Year
Surface Flow Wetland Systems			
Dows: aerated lagoon and wetland	$495,000	2.3	1991
Granger: aerated lagoon and wetland	$775,000	3.6	1986
Laurel: aerated lagoon and wetland	$900,000	1.2	1991
LeGrand: Sludge removal and wetland	$298,528	10	1992
Subsurface Flow Septic Tank System			
Buchanan County Fontana Campground	*$19,000	0.7	1998
IAMU	*$40,000		1999
Neil Smith Wildlife Refuge	*$150,000	0.124	1997
Subsurface Flow Septic Tank San			
Burr Oak	$637,436	0.24	1993

All costs are estimated except when actual costs were available and indicated with'. These cost are to provide guidance only and don't reflect up-to-day costs.

Cost data for systems located in Colorado similar to those for the above systems are presented in Table 9 in Chapter 3 Performance Expectations. All of the data show a wide variation in the cost per acre of wetlands as well as the pretreatment processes. This is not surprising when it is considered that very few were designed with the same treatment objectives; however, the data do provide a guide as to what the costs might be for constructed wetlands.

Operating and maintenance cost for constructed wetlands are limited and the most reliable data are summarized for four systems in Table 6:

Table 6. Annual Operation and Maintenance Costs for FWS Wetlands
(Crites and Lesley, 1998; WEF, 2001)

Location	Design Flow	Area	Annual Cost
	mgd	acres	$/acre
Cannon Beach, OR	0.68	16	4,500
Gustine, CA	1.00	24	819
Mt. Angel, OR	2.00	10	1780
Ouray, CO	0.36	2.2	1364

Power costs for aerated lagoon systems located in Colorado are available in the tables in Chapter 3 Performance Expectations. In practically all cases, power costs for the operation of wetland systems are limited to pumping and the pretreatment processes.

Construction and operating costs make lagoon/constructed wetlands system very attractive to small communities throughout the world. In addition, energy savings associated with these processes are a benefit to the community and the environment. Although not applicable to all small communities, there are few that will not benefit economically and environmentally.

Chapter 3. Performance Expectations

In general, BOD_5, Total Suspended Solids (TSS) and fecal coliforms (FC) removals in constructed wetlands have satisfied regulatory effluent requirements; however, there are many examples where they have failed to meet effluent standards. Frequently, this failure to meet the desired effluent quality can be attributed to the inadequate design of the pretreatment devices, the selection and management of vegetation, flow control structures or all of these. Two of the most frequent errors in the design of lagoon pretreatment systems are the design of surface overflow structures that transfer high concentrations of algae to the wetland and very long hydraulic residence times in the final or settling pond that encourages the growth of algae that is then transferred to the wetland. Obviously, algae naturally grow in wetlands and an additional burden of solids is not conducive to good performance.

BOD and TSS Removal

National Studies

BOD and TSS removals in FWS constructed wetlands from sites throughout the USA and one site in Canada are summarized in Table 7 (Crites, Middlebrooks and Reed; 2006):

Table 7. Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) Removal in Free Water Surface Constructed Wetlands

	Biochemical Oxygen Demand			Total Suspended Solids			References
Location	Influent	Effluent	Removal	Influent	Effluent	Removal	
	mg/L	mg/L	%	mg/L	mg/L	%	
Arcata, CA	26	12	54	30	14	53	Gearheart, et al. (1989)
Benton, KY	25.6	9.7	62	57.4	10.7	81	USEPA (1993a)
Cannon Beach, OR	26.8	5.4	84	45.2	8	82	USEPA (1993a)
Cle Elum, WA	38	8.9	77	32	4.8	85	Smith, et al. (2002)
Fort Deposit, AL	32.8	6.9	79	91.2	12.6	86	USEPA (1993a)
Gustine, CA	75	19	75	102	31	70	Crites (1996)
Iselin, PA	140	17	88	380	53	86	Watson, et al. (1989)
Listowel, Ontario, Canada	56.3	9.6	83	111	8	93	Herskowitz, et al. (1987)
Ouray, CO	63	11	83	86	14	84	Andrews (1996)
West Jackson County, MS	25.9	7.4	71	40.4	14.1	65	USEPA (1993a)
Sacramento County, CA	24.2	6.5	73	9.2	7.1 to 11.9	23 to 29	Nolte Associates (1999)

Excluding the Gustine and Iselin results, the systems on average significantly reduced the BOD and TSS in the wetland. It appears that as the TSS concentration approaches or exceeds 100 mg/L, wetlands have difficulty in producing an effluent concentration of less than 15 mg/L; however, wetlands are still capable of large reductions in the concentration of TSS at very high influent concentrations. The hydraulic residence times in the wetlands were not available and this may be a factor because a hydraulic residence time of 6 to 8 days may be required to achieve good TSS removal. BOD removals with influent concentrations of less than 100 mg/L produce excellent effluents of less than 10 mg/L.

Colorado Study

A summary of the characteristics of pretreatment facilities for lagoon/FWS and lagoon/SSF constructed wetlands systems are shown in Tables 8a through 8c:

Table 8a. Characteristics of Pretreatment Facilities in Colorado Lagoon/Free Water Surface and Subsurface Flow Constructed Wetlands
(Colorado Governor's Office of Energy Management and Conservation, 2001)

		Pretreatment						
Location	**Type**	**Design Flow Rate**	**Average Flow Rate**	**Surface Area**	**Total Volume**	**Depth**	**HRT**	**Aeration**
		mgd	mgd	acres	MG	ft	days	HP
Free Water Surface Wetlands								
Crowley Elevation 4,354 ft	Cell # 1	0.170	0.126	1.010	1.570	5.5	9.2	36
	Cell # 2			0.874	1.313	5.5	7.7	10.000
	Cell # 3			0.472	0.658	5.3	3.9	5.000
	Cell # 4			0.534	0.723	5.1	4.3	NA
Crowley Correctional Facility Elevation 4,354 ft	Cell # 1	0.150	0.110	0.847	1.9	10	12.6	60
	Cell # 2			0.847	1.9	10	12.6	15
	Cell # 3			0.244	0.4	10	2.7	NA
Delta Elevation 4,977 ft Lift Station, 5 HP	Cell # 1	0.067	0.038	0.309	0.597	9.51	8.8	16
	Cell # 2			0.336	0.653	9.55	9.7	6
	Cell # 3			0.224	0.392	9.29	5.8	2
Dove Creek Elevation 6,844 ft	Fermen. Pit	0.115	0.035	0.135	0.747	18	13	36
	Cell # 1			0.108	1.83	8	30	10
	Cell # 2			0.919	2.06	8	34	5
	Cell # 3			0.103	0.15	11	2.2	NA
La Veta Elevation 6,910 ft	Cell # 1	0.125	0.075	1.06	1.554	4.85	17.5	3
	Cell # 2			2.71	3.972	4.85	44.8	NA
	Cell # 3			0.996	1.674	5.5	18.9	NA

Table 8b Characteristics of Pretreatment Facilities in Colorado Lagoon/Free Water Surface and Subsurface Flow Constructed Wetlands

Location	Type	Design Flow Rate	Average Flow Rate	Surface Area	Total Volume	Depth	HRT	Aeration
		mgd	mgd	acres	MG	ft	days	HP
Manzanola Elevation 4,230 ft	Cell # 1	0.125	0.045	1.18	1.559	5	12.5-36	12
	Cell # 2			0.28	0.339	5	2.7-7.6	NA
Ouray Elevation 7,700 ft Pop. 700 winter, 2000 summ	Cell # 1	0.363	0.26	0.433	2.09	14.8	5.8-8.4	30
	Cell # 2			0.388	1.81	14.3	5.0-7.2	15
Platteville Elevation 5,100 ft	Cell # 1	0.348	0.25	1.5	2	5	5.75	12
	Cell # 2			4.1	4.9	4	14.1	NA
Silt Elevation 5,700 ft	Cell # 1	0.236	0.11	Approx. 3.4	5	5	Approx. 21.4	20
	Cell # 2			Approx.4.1	6.3	5	Approx. 26.9	15
	Cell # 3			Approx. 1.4	2	5	Approx. 8.7	NA
							Total 57 d	
Subsurface Wetlands								
Calhan Elevation 6,541 ft	Cell # 1	0.08	0.065	0.271	0.536	12	6.7	14
	Cell # 2			0.271	0.536	12	6.7	14
	Cell # 3			0.271	0.536	12	6.7	NA
Hi-Land Acres W&S District Elevation 5,144 ft	Cell # 1	0.055	0.022	0.226	0.4	12	6.6	30
	Cell # 2			0.226	0.4	12	6.6	30
	Cell # 3			0.224	0.23	8	4	NA

Table 8c Characteristics of Pretreatment Facilities in Colorado Lagoon/Free Water Surface and Subsurface Flow Constructed Wetlands

Location	Type	Design Flow Rate	Average Flow Rate	Surface Area	Total Volume	Depth	HRT	Aeration
		mgd	mgd	acres	MG	ft	days	HP
Las Animas Elevation 3,887 ft	Cell # 1	0.5	0.25	12.4	16.56	4.1	7	100
	Cell # 2			12.4	16.56	4.1	6.6	14
	Cell # 3			5.74	11.22	6	2.9	7.5
Rocky Mountain Shambhala Center Facility Elevation 7,800 ft	Septic Tanks	0.05	Seasonal	Individual septic tanks for each building	NA	NA	NA	NA
				Eff. Conveyed to six 2,200 gallon septic tanks				

Further details from the study by the Colorado Governor's Office of Energy Management and Conservation can be obtained from the address shown in the References. Aerated lagoons preceded all of the FWS wetlands, and the SSF wetlands were preceded by septic tanks or aerated lagoons. The systems were small with the design flow rates ranging from 0.067 to 0.363 mgd. All of the lagoon systems have long hydraulic residence times in the final cell that could have led to the production of high concentrations of algae in the effluent. Unfortunately, separate performance data for the lagoons and wetlands were not available; therefore, an accurate assessment of the two components of the system could not be made.

A summary of the characteristics of the constructed wetlands and the BOD, TSS and FC removals in the lagoons/wetlands systems are shown in Tables 9a and 9c. (Colorado Governor's Office of Energy Management and Conservation):

Table 9a Characteristics of Facilities, Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS)

Removal in Colorado Lagoon/Free Water Surface and Subsurface Flow Constructed Wetlands

Free Water Surface Wetlands

	Free Water Surface and Subsurface Wetlands				Construction and Power Costs		Average Biochemical Oxygen Demand*			Average Total Suspended Solids*			Effluent
Location	Area	Depth	Hydraulic Residence	Vegetation	System Power Consumption	Construction Costs System	Facility Influent	Wetland Effluent	Removal	Facility Influent	Facility Effluent	Removal	FC
	acres	feet	Time, days		kWh/yr		mg/L	mg/L	%	mg/L	mg/L	%	org/100mL
Crowley Elevation 4,354 ft	3.042	approx. 1	6	98% cattail	333,154	$350,000	220	22	90	489	29	94	717
	2 cells			3% duckweed									
Crowley Correctional Facility Elevation 4,354 ft	3.31	0.25	7.2	90% Cattail Reed canary grass, duckweed and creeping spikerush	489,933	Not Available	278	13	95	333	15	95	1075
	2 cells			10%									
Delta Elevation 4,977 ft Lift Station, 5 HP	1.377	2	5	95% Cattail	189,441	Not Available	277	15	95	94	39	59	<500
	1 cell divided by baffle into 2 cells			5% Baltic rush, Foxtail barley and tamarisk									
Dove Creek Elevation 6,844 ft	1 ac total	-	-	75% vegetation Cattail Only	333,154	$363,000	294	52	82	342	66	81	<1000
	4 FWS cells followed by 1 SF cell												
	Approx. ¾ area in FWS												
La Veta Elevation 6,910 ft	1.6	0.5 to 1 during winter	11.9 winter	95% water	108,000	$365,000	217	20	91	245	26	89	<2000
	2 cells	2 max	5 summer	5% cattail		Wetlands Only 1992	Ammonia-N	7.6 but ranged from 1 to 22 during two yr					

								monitorin g period					
Manzanola Elevation 4,230 ft	2.3	1	6	45% vegetation cattail	78,390	Not Available	211	23	89	121	34	72	<1000
	2 cells												
Ouray Elevation 7,700 ft	1.51	1.5	2 summer	80-90% cattail	293,960+	Not Available	96	4	96	139	7	95	1300
	2 cells		2.9 winter		lift station								
Platteville Elevation 5,100 ft	3	2 max.	6 summer	97 % cattail	78,389	Not Available	271	26	90	272	30	89	1009
	2 cells		1.6 winter										
Silt Elevation 5,700 ft	0.83			Cell 1 50% cat & duck	228,635	Not Available	229	30	87	202	27	87	<3000
	3 cells			Cell 2 80% duck, 20% cat									
				Cell 3 80% cat, 20 duck									
Subsurface Wetlands													
Calhan Elevation 6,541 ft	0.62	3	2.1	Cell 1 Has settled 8 inches to 1 foot, 30% water, 20% rock and 50% vegetation. Plant community 1 contained 60% cattail, duckweed and barnyard grass with a few foxtail barley. Plant community 2 contained 40% pinkweed, curly dock and Canada thistle with plains cottonwood, crack willow and prickly lettuce, but not dominant.	182,908	Not Available	245	11	96	241	6	98	<500
	2 cells												
	Gravel Size=3/4"												
	Void Space=28%												

Table 9b Characteristics of Facilities, Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS)

Removal in Colorado Lagoon/Free Water Surface and Subsurface Flow Constructed Wetlands

	Free Water Surface and Subsurface Wetlands				Construction and Power Costs		Average Biochemical Oxygen Demand*			Average Total Suspended Solids*			Effluent
Location	Area	Depth	Hydraulic Residence	Vegetation	System Power Consumption	Construction Costs Systems	Facility Influent	Wetland Effluent	Removal	Facility Influent	Facility Effluent	Removal	FC
	acres	feet	Time, days		kWh/yr		mg/L	mg/L	%	mg/L	mg/L	%	org/100mL
Hi-Land Acres W&S District Elevation 5,144 ft	0.21	4.5	5.6	Plant community 1 represents 90% of total cell area and is dominated by prickly lettuce and ragweed.	391,950	$250,000	194	6	97	172	11	94	<500
	Gravel Size=3/4"			Plant community 2 is dominated by cattail and lady's thumb.									
	Void Space=28%												
Las Animas Elevation 3,887 ft	NA	1 approx.	NA	Plant community 1 represents 80% of total cell area and is dominated by cattail, narrow leaved cattail, and softstem bulrush. Curley dock, witchgrass and switch grass are present but not dominent.	793,690	NA	176	17	90	240	24	90	<5,000
	Gravel Size=3/4"			Plant community 2 represents 20% of total cell and is dominated by cattail, softstem bulrush and ragweed with tamarisk and gumweed present but not dominant.									
	Void Space=NA												
Rocky Mountain Shambhala Center Facility Elevation 7,800 ft	0.23	1.8	NA	In Cells 1 and 2, vegetation was less than 30%. Cattail was dominant. Other species include bulrush, Nebraska sedge, beaked sedge and wild iris. Willow and chokeberry have been planted in less saturated areas of the wetland.	0	Wetland Only	130-310	4-190	Varies	40-76	16-40	Varies	11-98,000
	2 Cells					$200,000							
	Gravel Size=NA												
	Void Space=38												

*Although the average values frequently satisfy effluent standards, there were wide flucuations in the effluent concentrations.

With the exception of the Dove Creek system, on an average basis the systems satisfied the state effluent standard of 30 mg/L of BOD, but results tended to exceed the standards on an individual analysis basis. Effluent TSS limits were 75 mg/L for all of the systems except the Ouray system where the standard was 30 mg/L. TSS effluent limits were satisfied by all of the systems including the Ouray system after an initial acclimation period. Ouray performance indicates that with proper design constructed wetlands can produce excellent effluents.

Iowa Wetlands Study

A summary of the characteristics of twenty FWS and SSF constructed wetlands in Iowa inventoried by the Iowa Energy Center and Iowa Association of Municipal Utilities (2001) is shown in Tables 10a and 10b:

Table 10a. Inventory of Iowa NPDES Permitted Constructed Wetlands for Wastewater Treatment Conducted in 2000-2001

(Iowa Energy Center and Iowa Association of Municipal Utilities, 2001)

Wetland	Startup Year	Location	Wastewater System	Type of Wetland	Number of Cells and Dimensions	Depth and Type of Media	Liner	Design and Actual Flow System	Flow/Ac	Final Discharge
								(mgd)	(gal/Ac)	
Agency STP Pop. 616	1994	Wapello County, Southeast IA	2 aerated lagoons, 1 non-aerated lagoon, continuous flow	Surface Flow; open	1 Cell - 3.5 Acre	Native soil	Native soil	0.06 design, 0.03 actual	Design flow/Acre	Cedar Creek
Blencoe STP Pop. 250	1998	Monona County, West Central IA	2 facultative lagoons, winter storage	Surface Flow; open and vegetated	2 Cells - 1.84 Acre, 40,075 ft^2 each	6" Native soil	Native soils	0.03 actual (No discharge out of wetlands during summer of 2000)	0.016	McNeil ditch to Monona Harrison
Buchanan County Fontana Campground Seasonal	1998	Buchanan County, Northeast IA	Septic Tank effluent from bathhouse and dump station, 6 mounts	Subsurface Flow	1 Cell - 0.07 Acre, 3000 ft^2	12" Washed pea gravel, 12" mulch on top	Synthetic (45 ml)	0.001 design	0.014	Natural Wetland then to Otter Creek
Burr Oak STP Less than 100 pop.	1993	Winneshiek County, Northeast IA	20,000 gal septic tank to two sand filters to wetland	Subsurface Flow	1 Cell - 0.24Acre, 250 ft x 4l ft	11" Gravel	On-site clay	0.0 18 actual	0.075	Silver Creek
Chelsea STP Pop. 336	990	Tama County, East Central IA	2 aerated lagoons, continuous flow	Surface Flow; open and vegetated	2 Cells - 0.26 Acre, Each 155 ft x 37 ft	18" Native soil	Unlined	0.043 design, 0.022 actual	0.16	Unnamed tributary to Otter Creek
Dows STP Pop. 660	1991	Wright County, Central IA	1° and 2 ° aerated lagoons, continuous flow	Surface Flow; open and vegetated	I Cell - 2.3 Acres, 100,188 ft^2	Native soil	Native soils	1.09 design, 0.105 actual	0.47	Iowa River
Four Oaks Group Home Bertram (System just approved)	2001	Linn County, Eastern IA	2 septic tanks, 1 collector tank, 1 dosing tank to 4 Multi-Flo units	Subsurface Flow	2 Cells - 0.03 Acre, each 600 ft^2	Under construction	Under Construction	0.006 design		
Granger STP Pop. 624	1986	Dallas County, Central IA	1° and 2 'aerated lagoons, continuous flow	Surface Flow; vegetated	2 Cells - 3.6 Acres, Total 156,816 ft^2	Native sand and silty clay soils, alluvial	Unlined	0.420 design, 0.125 actual	0.58	Beaver Creek
IAMU Variable pop.	1999	Polk County, Central IA	Septic tank effluent from training complex	Subsurface Flow	1 Cell (kidney-shaped – 0.15 Acre, 49 ft x 139 ft x 44 ft x 128 ft	18" of 1" Crushed gravel overlain by 6"	Bentonite	0.003 design, .000133 actual	0.02	Carney Marsh to Four Mile Creek
Iowa City STP Pop. 60,148	1998-99	Johnson County, Eastern IA	Activated sludge plant, post chlorinated effluent to wetland	Surface Flow; vegetated, treated only a portion of plant flow for study	4 Cells (rectan-gular) - 0.55 Acre, 20 ft x 300 ft	Native soil	Unlined	0.029 actual	0.52	Iowa River

(Research study on performance of wetland species on performance of wetland species)

Table 10b Inventory of Iowa NPDES Permitted Constructed Wetlands for Wastewater Treatment Conducted in 2000-2001
(Iowa Energy Center and Iowa Association of Municipal Utilities, 2001)

Wetland	Startup Year	Location	Wastewater System	Type of Wetland	Number of Cells and Dimensions	Depth and Type of Media	Liner	Design and Actual Flow System	Flow/Ac	Final Discharge
								(mgd)	(mgd/Ac)	
Lake Park STP Pop. 996	1997	Dickinson County, Northwest IA	1° to 2° facultative lagoons, winter storage	Surface Flow, open and vegetated	1 Cell (L-shaped, with windy flow) - 9 Acres, 392, 040 ft2	18" Native soil, Webster, Clarion, Nicollet	Bentonite	0.125 design, 0.11 actual	Design flow / Acre 0.014	West Fork Little Sioux River
Lake Vista Motel (Out of business as of 1998)	1997	Lucas County, Southern IA	2,000 gallon septic tank	Subsurface Flow, vegetated and surface flow, open	1 Subsurface Flow Cell 25'x 125' followed by 3 Surface Flow Cells, 0.88 Acre, 35 ft x 250 ft, 30 ft x 450 ft, 40 ft x 320 ft	6" of 3/8" Gravel with a underlay of 18" of 3/4" gravel	Unlined, native clay soils	0.002 design	0.002	Lake Ellis
Laurel STP Pop. 581 (Combined with Haverhill and Ferguson)	1991	Marshall County, Central IA	2 aerated lagoons in series, continuous flow in series	Surface Flow, vegetated	2 Cells (parallel) - 0.6 Acre each, 88 ft x 308 ft	Native soils	Unlined, drainage tile	0.074 design, 0.013 actual	0.06	2 Unnamed drainage ditches to Snipe Creek to Lates Creek to South Timber Creek
LeGrand STP Pop. 854	1992	Tama County, Northeast IA	2 facultative lagoons, continuous flow	Surface Flow, open and vegetated	2 Cells (with windy flow, dikes) - 10 Acres total	Native silty to clayey soil	Native soils	0.315 design, 0.18 actual	0.032	Iowa River
Maharishi Resort Variable pop.	1993	Jefferson County, Southeast IA	SBR, continuous flow	Surface Flow, open	1 Cell - 0.23 Acre, 95 ft x 110 ft	Unknown	Unknown	0.02 design, 0.011 actual	0.09	Unnamed Creek
Norwalk STP (No longer used replaced by Biolac)	1988	Warren County, South Central IA	1° to 2 ° facultative lagoons	Surface Flow, open	2 Cells - 14.4 Acres each, 627,264 ft2 each	Native soil, 7.75 ft water depth	Unlined	0.4 design, 0.300 actual	0.03	North River Drainage Swale
Norway STP Pop. 583	1992	Benton County, Eastern IA	2 aerated lagoons, continuous flow	Surface Flow, vegetated with open areas	3 Cells - Approx. 2 Acres, 86,400 ft2 total	Native soil	Lined with native soil	0.05 actual, 0.0622 actual	0.03	Mud Creek
Riverside STP Pop. 928	1981	Washington County, Eastern IA	1 facultative 3- cell lagoon	Non-engineered surface flow	Diked natural wetland	Native soil	Non-engineered	Non-engineered	N/A	English River
Springbrook State Park (System over designed)	2000	Guthrie County, Central IA	2 aerated lagoons, system being redesigned	Surface Flow	2 Cells - 0.28 Acre, 50 ft x120 ft, each	Unknown	Unknown	0.005 design (No discharge to wetland yet)	0.018	Raccoon River
Neil Smith Wildlife Refuge Variable	1997	Jasper County, Central IA	Septic tank effluent from visitors center	Subsurface Flow	3 Cells (load and rest cells) - 0.37 Acre, 180 ft x30 ft, 5400 ft2 each	12" Pea gravel	Synthetic - 30 ml, rock riprap along berm	0.013 design	0.035	Walnut Creek

Copies of the report can be obtained from the address given in the References. As with the Colorado wetlands, the systems are small and the design flow rate ranges from 0.002 to 0.315 mgd. All of the SSF wetlands used septic tanks for pretreatment while the FWS wetlands were preceded by aerated lagoons with the exception of the Iowa City Sewage Treatment Plant which discharged secondary effluent to the wetland to evaluate wetland species.

Carbonaceous BOD (CBOD) removal for systems with influent and effluent data are shown in Figure 5:

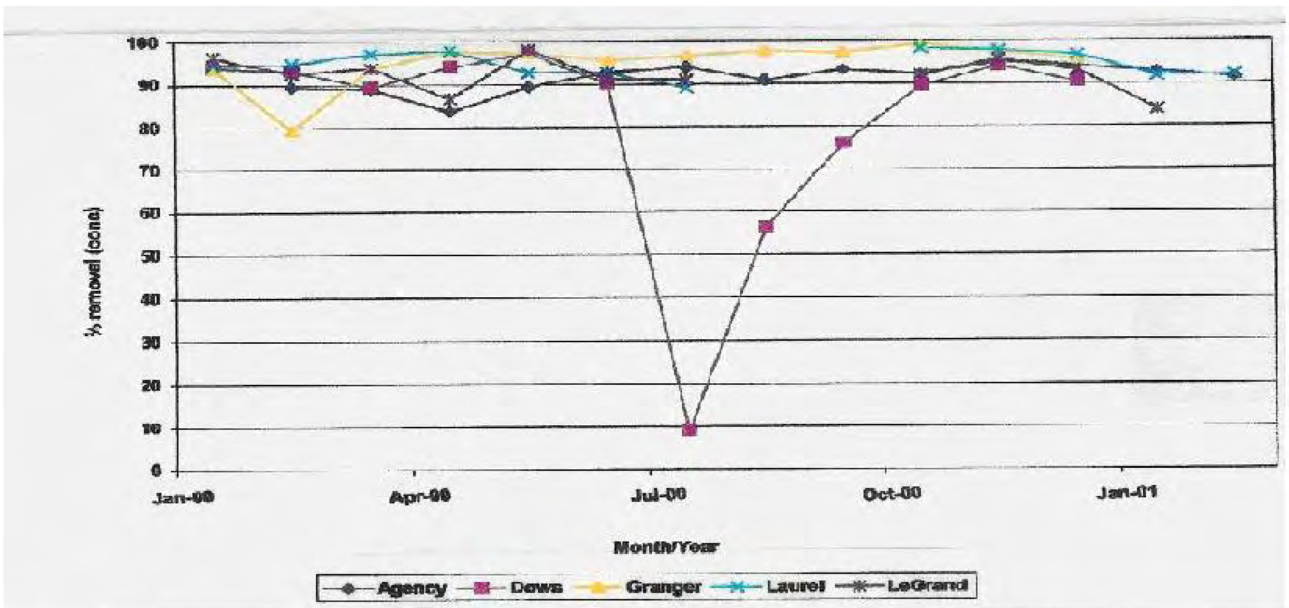


Figure 5. Carbonaceous BOD (CBOD) Removal in Iowa Systems with Influent and Effluent Data (Iowa Energy Center and Iowa Association of Municipal Utilities, 2001)

and TSS removal is presented in Figure 6:

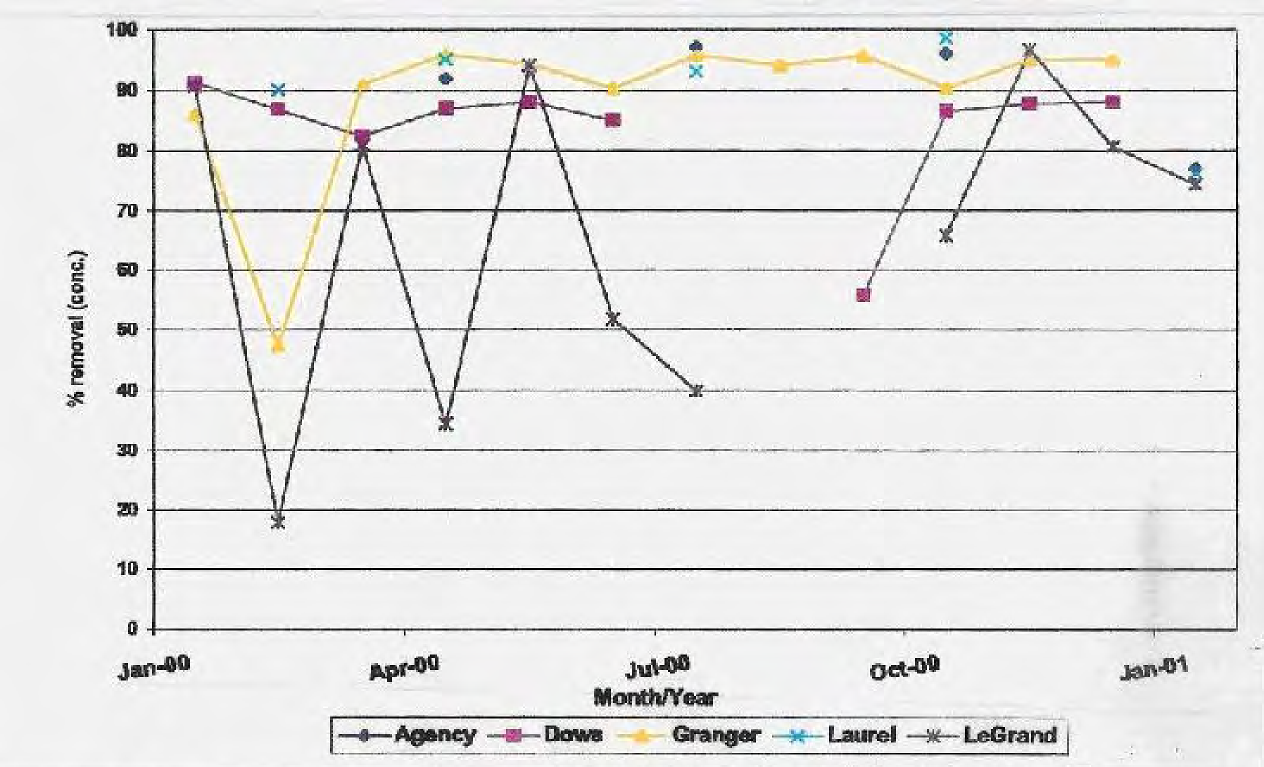


Figure 6. Total Suspended Solids Removal in Iowa Systems with Influent and Effluent Data (Iowa Energy Center and Iowa Association of Municipal Utilities, 2001)

With the exception of the Dows system, CBOD removal exceeded 85%, but TSS removal was very erratic in the Dows and LeGrand Systems. TSS removal in the other systems appeared to be very good.

Nitrogen Conversion and Removal

Ammonia-N conversion in constructed wetlands has varied significantly, and this variation frequently is related to the anoxic/anaerobic conditions in heavily vegetated systems. Where significant open water between sections of heavy vegetation have occurred in conjunction with low surface loading rates of nitrogen, significant nitrogen removal has been observed. Nitrogen conversion data for wetlands are relatively limited because many state regulatory agencies have not required that the data be collected.

National Studies

Ammonia-N and total nitrogen removals in FWS constructed wetlands throughout the USA and one location in Canada are shown in Table 11:

Table 11. Ammonia Nitrogen and Total Nitrogen Removal in FWS Wetlands
(Crites and Tchobanoglous, 1998)

Location	Type of Watewater	Ammonia-N Influent	Ammonia-N Effluent	Total Nitrogen Influent	Total Nitrogen Effluent	References
		mg/L	mg/L	mg/L	mg/L	
Arcata, CA	Oxidation Pond	12.8	10	-	11.6	Gearheart et al. (1989)
Beaumont, TX	Secondary	12	2	-	-	USEPA (1999)
Iselin, PA	Oxidation Pond	30	13	-	-	Watson etal. (1989)
Jackson Bottoms, OR	Secondary	9.9	3.1	-	-	
Listowel, Ontario, Canada	Primary	8.6	6.1	19.1	8.9	Herskowitz et al. (1987)
Pembroke, KY	Secondary	13.8	3.35	-	-	
Sacramento County, CA	Secondary	14.9	9.1	16.9	11.0	Nolte Associates (1999)
Salem, OR	Secondary	12.9	4.7	-	-	City of Salem, OR (2003)

Removal of ammonia-N varied widely and this variation is probably attributable to the amount of open water present in the wetlands.

Colorado Study

The State of Colorado study by the Governor's Office of Energy Management and Conservation (2001) only include ammonia-N removal data for the La Veta system where the average effluent ammonia-N concentration was 7.6 mg/L; however, the concentrations ranged from 1 to 22 mg/L during the two-year monitoring program.

Iowa Study

The Iowa study did provide data for ammonia-N conversion, and the main conclusion was that conversion was limited to the warm months of the year for all of the systems studied with the exception of the Lake Park System that used winter storage of the effluent (Figure 7).

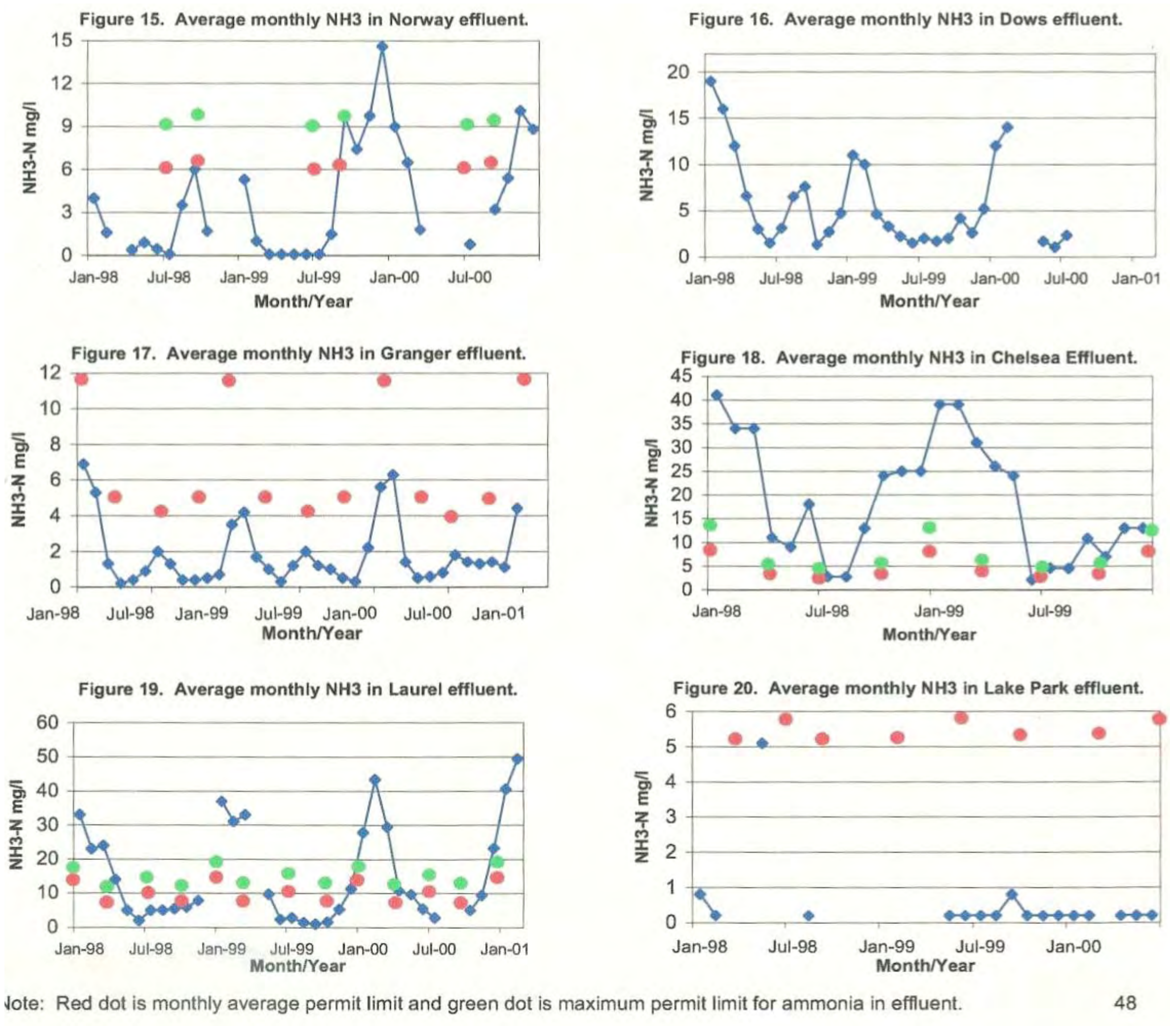
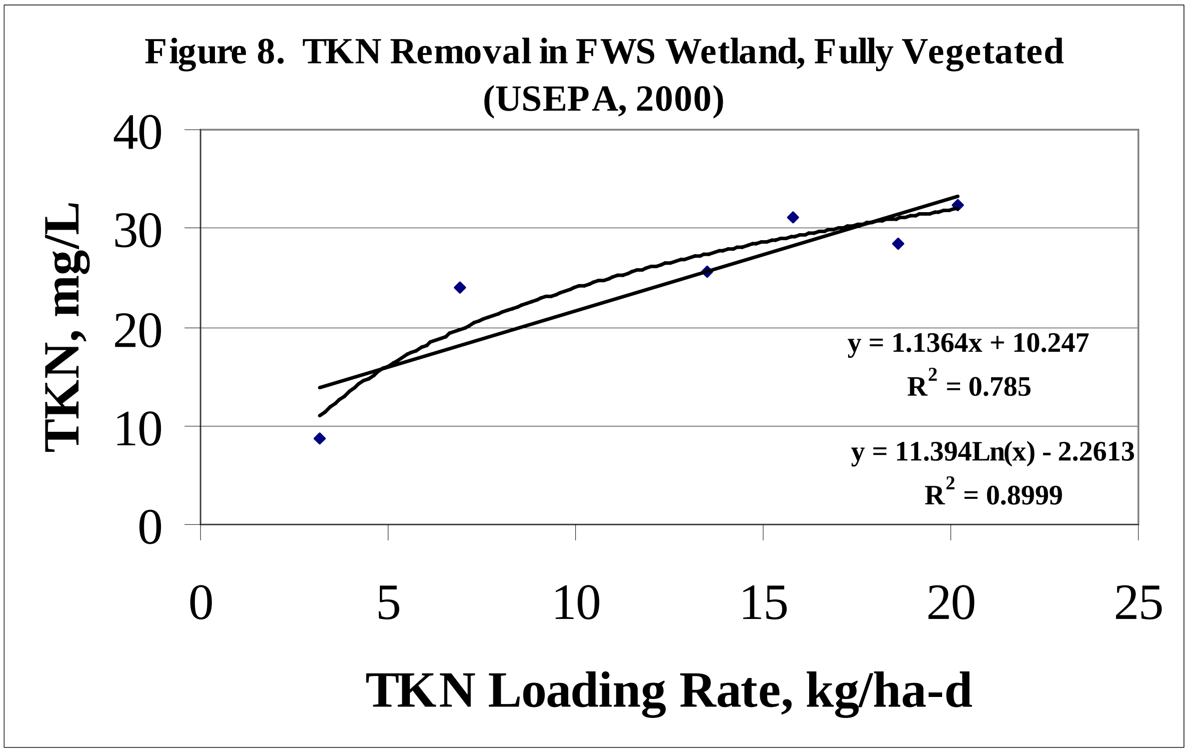


Figure 7. Ammonia-N Removal in Iowa Wetlands (Iowa Energy Center and Iowa Association of Municipal Utilities, 2001)
(Figure numbers shown above are the original numbers used by the IEW and IAMU)

As with the Colorado data, the removals reported were for the pretreatment component and the wetland combined. The Iowa Study ammonia-N average monthly values for six systems are shown in Figure 7.

EPA Report

Total Kjeldahl Nitrogen (TKN), which is composed of organic nitrogen and ammonia-nitrogen, also has been removed in wetlands with heavy vegetation and low loading rates as shown in Figure 8 (EPA 2000):



Both open water and low surface loading rates appear to be pertinent design parameters; however, the importance of open water appears to be the dominant factor in relatively highly loaded wetlands.

The plot shown in Figure 8 excluded a vegetated removal value (approximately 31.3 mg/L TKN and 3.1 kg/ha-d) appearing in the original EPA plot that appeared to be an outlier. A semi-log fit of the data yields the following equation that may serve as a guide in estimating TKN removal in fully vegetated constructed wetlands. The fit of the data yields a R^2 of 0.8999 that is highly significant.

$$EffluentTKN(mg/L) = 11.394 Ln(TKN\ \ surface\ load,(kg/ha-d)) - 2.2613$$

Using the above equation to estimate an effluent TKN concentration of less than 5 mg/L, the TKN surface loading rate would be 1.89 kg/ha-d. For an effluent of 20 mg/L of TKN, the surface loading rate would be 7.06 kg/ha-d. At this higher loading rate, it would be desirable to have considerable open water to nitrify the ammonia-N for denitrification in a later vegetated section of the wetland. If only nitrification were desirable, a higher loading rate with adequate open water would suffice.

A linear fit of the data shown in Figure 8 also was completed and the equation follows:

$$EffluentTKN(mg/L) = 1.1364(TKN\ \ surface\ load,(kg/ha-d)) - 10.247$$

The R^2 was 0.785 that is still significant but less than that for the semi-Ln fit. The surface loading rate for a TKN concentration of less than 5 mg/L would not be obtainable using the linear fit because the intercept of the line of best fit is greater than 10 mg/L.

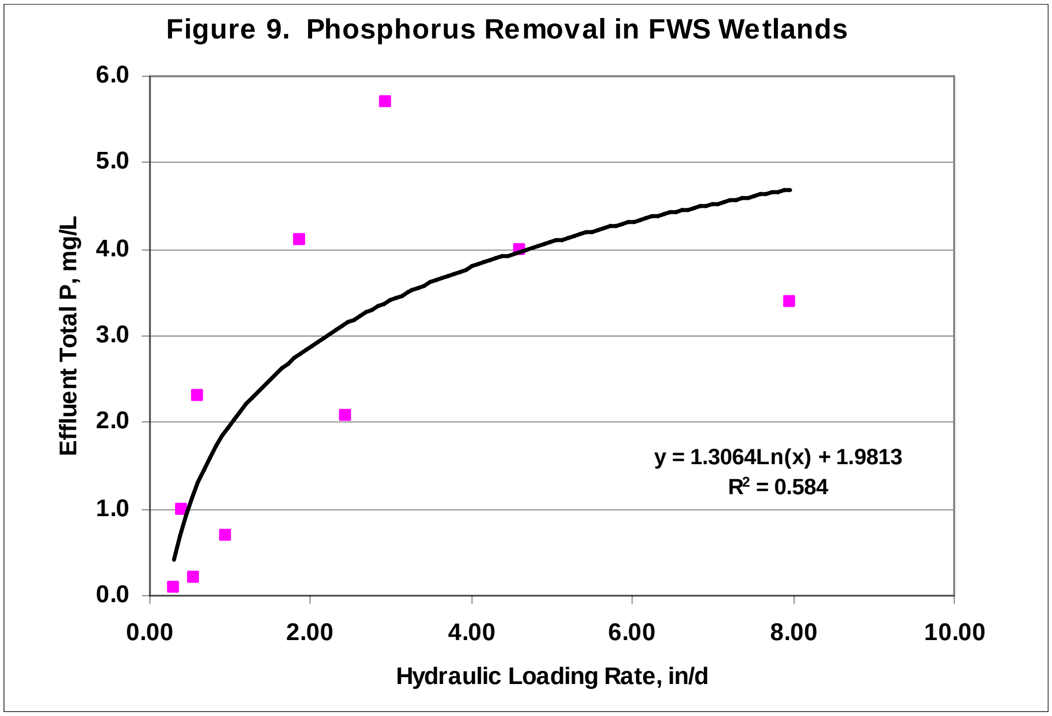
Phosphorus Removal

FWS wetland phosphorus removal data are limited and the available data for sites in the USA and one Canadian site are shown in Table 12:

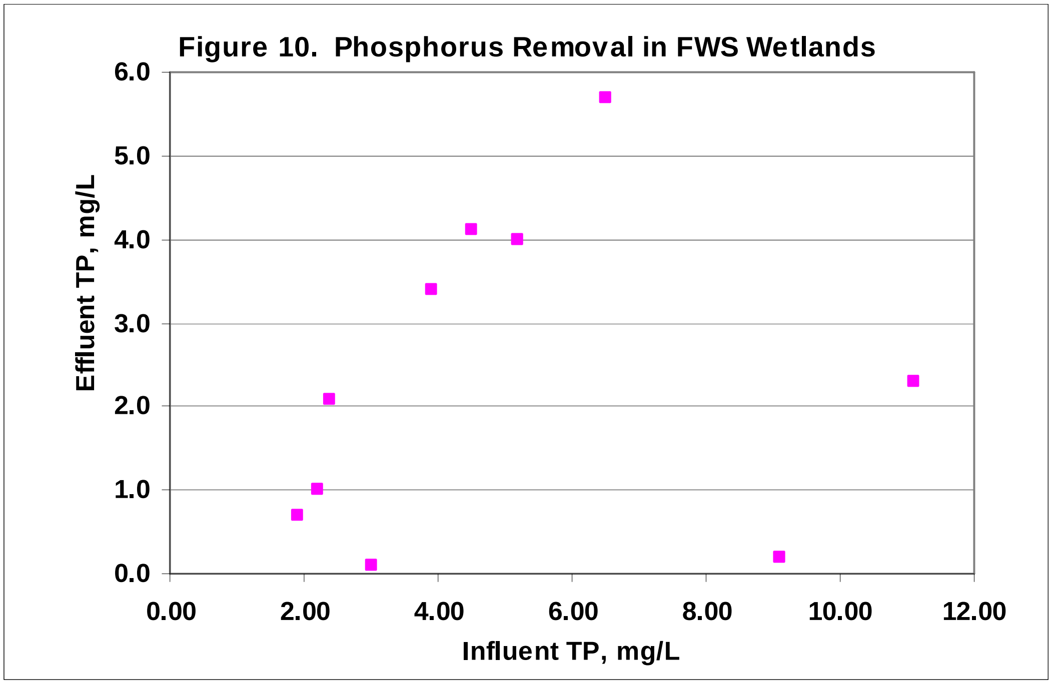
Table 12. Phosphorus Removal in FWS Wetlands(Crites, Middlebrooks and Reed, 2006)

Location	Hydraulic Loading Rate	Total Phosphorus Influent	Total Phosphorus Effluent	Percent Removal
	inches/day	mg/L	mg/L	%
Listowel, Ontario, Canada	0.95	1.90	0.7	62
Pembroke, KY	0.30	3.00	0.1	96
Sea Pines, SC	7.95	3.90	3.4	14
Benton, KY	1.86	4.50	4.1	10
Leaf River, MS	4.60	5.20	4.0	23
Lakeland, FL	2.93	6.50	5.7	13
Clermont, FL	0.54	9.10	0.2	98
Brookhaven, NY	0.59	11.10	2.3	79
Sacramento County, CA	2.45	2.38	2.1	13
Salem, OR	0.40	2.20	1.0	55

Phosphorus removal appears to be directly related to the hydraulic loading rate as shown in Figure 9:



The plot of effluent TP versus influent TP in Figure 10:



Indicates that above a surface loading rate of 0.59 inches/day the relationship is essentially linear with little TP removal occurring. This means that if significant TP removal is to occur a very large surface area must be provided.

Fecal Coliforms Removal

Effluent standards for fecal coliforms removal in constructed wetlands in Colorado varied from 1,500 to 6,000 organism/100 mL. Most of the systems satisfied the standards on an average basis, but all had an occasional excursion that exceeded the standards. This appears to be the case in most wetland throughout the USA. These excursions can be attributed to many factors including design influences and the effects of aquatic animals and birds.

Priority Pollutants, Heavy Metals and Pathogens

In addition the effective removal of the typical pollutants (BOD, TSS, Nitrogen, Phosphorus and Fecal Coliforms), constructed wetlands are very effective in the removal of organic priority pollutants, some heavy metals and pathogens. Organic priority pollutants removals in pilot scale FWS constructed wetlands with a 24-hr HRT ranged from 49% for 1,2-Dichloroethane to 99% for *p*-Nitrotoluene with most removals in the 80 to 90% range (Crites, Middlebrooks and Reed, 2006). Metals removal in FWS constructed wetlands ranged from 0 to 99% with arsenic and nickel removals nonexistent and other metals removal in the range of 46 to 99% (Crites, Middlebrooks and Reed, 2006). Pathogens removal in wetlands is very similar to that observed in lagoons systems with HRT greater than 20 days. Pathogen removals can be estimated with the following equation:

$$\frac{C_{pe}}{C_{p0}} = \frac{1}{\left[1 + \left(tK_T\right)\right]^n}$$

Where

C_{pe} = Effluent pathogen concentration, organisms/L

C_{p0} = Influent pathogen concentration, organisms/L

t = Actual hydraulic residence time, d

k_T = Temperature-dependent rate constant, d^{-1}

$k_T = 2.6(1.19^{)(T-20)}$

T = Mean water temperature in the wetland, ^0C

n = Number of cells in series

Chapter 4. Design Methods Comparison

There are several design equations and procedures available for constructed wetland design, but the comparisons shown in Table 13 for BOD removal and Table 14 for nitrification and nitrogen removal are the most used procedures and have a relatively long history of usage. The limitations of the four methods are briefly discussed below and in the tables, but details can be obtained in Crites, Middlebrooks and Reed (2006), USEPA (2000), Kadlec and Knight (1996) or the original references. Tables 13 and 14 were printed from two Microsoft Excel spreadsheet programs used to design various types of constructed wetlands.

The models based on areal loading (volume of water or mass of contaminant per day divided by the surface area of the wetland) and hydraulic residence time (volume of water per day divided by the volume of the wetland) should give similar results, but they do not. One reason is that the models are based on separate data sets. The data set for the areal model contained several lightly loaded wetlands that resulted in low reaction rates that would yield large areas when used in the model. In addition the background concentration (C*) and the safety factor (z) are used inside the LN function of the areal model and this causes significant increases in the land area required. The USEPA method and the Kadlec and Knight models are based on areal loading rates and give similar results (Tables 13 and 14). The USEPA method is based on the same empirical method of mass of constituent of concern applied per surface area used for many years to design facultative lagoons. The selection of the quantity of constituent to be applied to a given surface area is based on experience with similar systems rather than on a statistical analysis of data from a large database.

The limiting size of a wetland designed with the models is based on the constituent requiring the largest area. In most cases the limiting factors will be the nitrogen and phosphorus removal requirements.

Table 13. Wetland Design for BOD and TSS Removal Based on Reed Models, Kadlec and Knight Models

Crites and Tchobanoglous Models, and EPA 2000 Method

The following models are based on hydraulic residence time or volumetric loading rate. For a specific set of wetland conditions, the various models should yield similar results. They do not because the models were derived from different data sets. In addition the areal based model contains and internal background concentration (C*) and safety factor (z) within the LN function that results in large differences. The other models use an external background concentration and safety factor. The safety factor z is the ratio of the annual mean concentration to the maximum monthly concentration based on the data base used to develop the model. Porosity, water depth and HRT are not included in the areal model.

BOD Removal - Reed Model

Substitute Values in shaded Fields to Calculate Areas

Influent BOD = C_o =	100	mg/L		
Effluent BOD = C_e =	30	mg/L		
Flow Rate =	3785	m3/d	1.000	mgd
Depth of Wetland = y =	0.6	m		
Void Space = n =	0.75			
Theta =	1.06			
Temperature =	3	deg C		
k_{20} =	0.678			
Safety Factor =	25%			
k_T =	0.252			

$$A_s = \frac{Q(\ln C_0 - \ln Ce)}{K_T(y)(n)}$$

As = 50275 m^2

HRT = 5.98 days

Water Temperature ^{0}C	Area, ac (Includes 25% SF)	Area, m^2 (Includes 25% SF)	Hydraulic Residence Time, d
3	12.42	50275	5.98
6	10.43	42212	5.02

Algal solids may require 6 to 10 days of detention time for removal.

9	8.76	35442	4.21

TSS Removal - Reed Model

$C_e = C_o[0.1139 + 0.00213\ (HLR)]$ = Effluent TSS = 13.0mg/L

HLR = Hydraulic Loading Rate = 7.53cm/d
Co = influent TSS = 100mg/L

Wetland Area, m^2	Effluent TSS mg/L	HLR cm/d
50275	13.0	7.53
42212	13.3	8.97
35442	13.7	10.68

Kadlec and Knight Model for BOD Removal

$$\boxed{A = \frac{Q \ln\left[\dfrac{C_{BOD,i} - C_{BOD}*}{C_{BOD,0}z - C_{BOD}*}\right]}{k_{BOD}}}$$

Area = 163736m^2
40.46ac

HRT = 19.47d

Substitute Values in Shaded Fields to Calculate other Areas

k_{20} = Reaction Rate at 20 degrees C =	34	m/yr	
Theta = Temperature Coefficient =	1.04		
$C_{BOD,i}$ = Influent BOD Conc. =	100	mg/L	
$C_{BOD,0}$ = Eff. BOD Conc. =	30	mg/L	
C*BOD = Background	8.80	mg/L	
Temperature of Water =	6	deg. Celsius	
k_T =	19.634		
Q = Design Flow Rate =	3785	m^3/d	1.000mgd
Porosity =	0.75		
Depth =	0.6	m	
Safety Factor = z =	0.59		

Water Temperature ^0C	Area, ac	Hydraulic Residence Time, d
3	45.51	21.90
6	40.46	19.47
9	35.97	17.31

TSS Removal with Kadlec and Knight Model

K_{20} (m/yr) =	1000m/yr
θ =	1
C^* (mg/L) = 5.1 + 0.16(C_0).	
θ_z (for C^*) = [$C_T^* = C_{20}^* (\theta)(T–20)$] =	1.065
C_e = effluent TSS =	30mg/L
z = safety factor =	0.526
C^* =	21.1mg/L
C_T^* =	8.74mg/L

Area for TSS Removal =	3539m^2	0.8745acre

Crites and Tchobanoglous Model

BOD Removal

$$t = \frac{-\ln\left(\frac{C_e}{C_0}\right)}{K_T}$$

$$K_T = K_{20}\theta^{(T-20)}$$

$$A = Qt/dn$$

C_e =	30mg/L	
C_0 =	100mg/L	
K_{20} =	0.678d^{-1}	
Theta =	1.06	
T =	3^{0}C	
d = depth =	0.6m	
n = porosity =	0.75	
Q =	3785m^3/d	
Safety factor =	25%	
K_T =	0.252d^{-1}	
t =	4.78d	
Area =	40220m^2	9.94ac
Area + SF =	50275m^2	12.42ac

Free Water Surface Wetland Design - EPA Design Manual - September 2000

With some open water in the FWS wetland, higher loading rates can be used.

Flow Rate = Q =	3785	m^3/d	1.000 mgd
Influent BOD to Wetland = C_0 =	100	mg/L	
Influent TSS to Wetland =	100	mg/L	
BOD Loading Rate = Insert value to match effluent requirement =	60	kg/ha-day	
TSS Loading Rate = Insert value to match effluent requirement =	50	kg/ha-day	
Porosity in Zone 1 = p1 =	0.75	Do no enter zero if not occupied	
Porosity in Zone 2 = p2 =	1	Do no enter zero if not occupied	
Porosity in Zone 3 = p3 =	0.75	Do no enter zero if not occupied	
Porosity in Zone 4 = p4 =		Do no enter zero if not occupied	
Porosity in Zone 5 = p5 =		Do no enter zero if not occupied	
Average Porosity =	0.8333		
Depth in Zone 1 = d1 =	0.6	Do no enter zero if not occupied	
Depth in Zone 2 = d2 =	1.2	Do no enter zero if not occupied	
Depth in Zone 3 = d3 =	0.6	Do no enter zero if not occupied	
Depth in Zone 4 = d4 =		Do no enter zero if not occupied	
Depth in Zone 5 = d5 =		Do no enter zero if not occupied	
Average Depth =	0.8		

Solution

ALR = areal loading rate = QC_0/Aw

Fully Vegetated FWS Wetland			FWS Wetland with Significant Opem Water		
Parameter	Zone 1 Areal Loading	Effluent Conc.	Parameter	Areal Loading	Effluent Conc.
BOD	40 kg/ha-d	30 mg/L	BOD	45 kg/ha-d	<20 mg/L
TSS	30 kg/ha-d	30 mg/L		60 kg/ha-d	30 mg/L
			TSS	30 kg/ha-d	<20 mg/L
				50 kg/ha-d	30 mg/L

Area required for BOD Loading

A_w = total area of FWS = 6.31 ha 15.59 acres

Area required for TSS Loading

A_w = total area of FWS = 7.57 ha 18.71 acres

Divide Total Area into Zones

Fraction of Area in Zone 1 = 0.333

Fraction of Area in Zone 2 =	0.333	
Fraction of Area in Zone 3 =	0.333	
Fraction of Area in Zone 4 =	0	
Fraction of Area in Zone 5 =	0	
Controlling Area =	7.57ha	18.71acres
Area in Zone 1 =	2.52ha	6.23acres
Area in Zone 2 =	2.52ha	6.23acres
Area in Zone 3 =	2.52ha	6.23acres
Area in Zone 4 =	0.00ha	0.00acres
Area in Zone 5 =	0.00ha	0.00acres
Volume in Zone 1 =	15125m^3	4.00MG
Volume in Zone 2 =	30250m^3	7.99MG
Volume in Zone 3 =	15125m^3	4.00MG
Volume in Zone 4 =	0m^3	0.00MG
Volume in Zone 5 =	0m^3	0.00MG
Total Volume =	60499m^3	15.98MG
HRT in Zone 1 at average Q =	3.00days	
HRT in Zone 2 at average Q =	7.99days	
HRT in Zone 3 at average Q =	3.00days	
HRT in Zone 4 at average Q =	0.00days	
HRT in Zone 5 at average Q =	0.00days	
Total HRT =	13.99days	
Average HRT =	13.32days	
Peaking Factor, Monthly =	2	
HRT Average at Peak Flow	6.66days	
HRT in Zone 1 at Peak Flow =	1.50days	
HRT in Zone 2 at Peak Flow =	4.00days	
HRT in Zone 3 at Peak Flow =	1.50days	
HRT in Zone 4 at Peak Flow =	0.00days	
HRT in Zone 5 at Peak Flow =	0.00days	

HRT of 2 days minimum is recommended in Each Cell at Peak Monthly Flow

Design HRT

HRT in Zone 1 at Design Peak Flow =	2.00days
HRT in Zone 2 at Design Peak Flow=	4.00days
HRT in Zone 3 at Design Peak Flow =	2.00days
HRT in Zone 4 at Design Peak Flow =	0.00days
HRT in Zone 5 at Design Flow =	0.00days
HRT in Zone 1 at Average Flow Q =	4.00days
HRT in Zone 2 at Average Flow Q =	7.99days
HRT in Zone 3 at Average Flow Q =	4.00days
HRT in Zone 4 at Average Flow Q =	0.00days
HRT in Zone 5 at Average Flow Q =	0.00days

Design Volume & Surface Area for EPA Design

	Volume	Surface Area		Running Totals
	m^3	m^2	acres	acres
Zone 1	15140	25233	6.24	6.24
Zone 2	30250	25208	6.23	12.46
Zone 3	15140	25233	6.24	18.70
Zone 4	0	#DIV/0!	#DIV/0!	#DIV/0!
Zone 5	0	#DIV/0!	#DIV/0!	#DIV/0!
Total	60530			

Reed Model				Kadlec and Knight Model			
Water Temperature ^0C	Area, ac (Includes 25% SF)	Area, m^2 (Includes 25% SF)	Hydraulic Residence Time, d	Water Temperature ^0C	Area, ac	Area, m^2	Hydraulic Residence Time, d
3	12.42	50275	5.98	3	45.51	184181	21.90
6	10.43	42212	5.02	6	40.46	163736	19.47
9	8.76	35442	4.21	9	35.97	145561	17.31

Table 14. Comparison of Various Methods Used to Predict Nitrogen Removal in Constructed Wetlands

See BOD Removal Table for Limitations of the Various Models

Reed Design Models for Nitrogen Removal

Determine the FWS area required for ammonia removal.

$$A_s = \frac{Q(\ln C_0 - \ln Ce)}{K_T(y)(n)}$$

Where

A_s = surface area of FWS wetland m^2
K_T = temperature-dependent, first-order rate constant, d^{-1}
K_T = 0 d-1 (0oC) 0
= 0.2187 (1.048)(T-20), d^{-1} 1+ ^{o}C 0.1368
n = "porosity" of the wetland 0.65 - 0.75 (lower number for dense, mature vegetation)
C_o = influent TKN concentration, mg/L
C_e = effluent ammonia concentration, mg/L
Q = average flow in the system m^3/d
y = average water depth in the system, m
t = hydraulic residence time, d

Enter in data

T =	10°C		
FWS n =	0.75	SF n =	0.32
Q =	3785 m^3/d	0.9999MGD	
C_o =	20mg/L	Pre-treatment process effluent	
C_e =	5mg/L		
FWS y =	0.6m	SF y =	0.46m
Nitrification K_T =	0.136847213 d^{-1}		

Determine the size and detention time for nitrification in the FWS wetland:

$$A_s = \frac{Q \ln\left(\frac{C_0}{C_e}\right)}{K_T\, y n}$$

Surface Area: A_s = 85207 m^2 = 21.05 acres
HRT: t = 10.1 d

Safety Factor = 25%

Surface Area + Safety Factor = 106508 m^2 26.32 ac
HRT + Safety Factor = 12.7 d

Above surface area and HRT are for nitrification only. Must check to determine if size adequate for denitrification

Determine the effluent nitrate concentration after denitrification

Nitrate to be denitrified = C_0-C_e

Nitrate to be denitrified = 15 mg/L

K_{20} for denitrification = 1 d^{-1}

K_T = K20(1.15)(T-20)

K_T for denitrification = 0.2472 d^{-1}

$$\boxed{\frac{C_e}{C_0} = \exp(-K_T t)}$$

C_e = Effluent Nitrate = 0.656 mg/L

Determine effluent TN:

Effluent TN = Effluent nitrate + Effluent ammonia

Effluent TN = 5.66 mg/L

If the TN is less than the permit, then the area and the hydraulic detention time are OK; otherwise must try another iteration.

Determine the surface area and detention time for the subsurface wetland

For the SF wetland, determine KNH for various percent root zone using the following equation

K_{NH} =	0.01854 + 0.3				
K_{NH} =	nitrification				

rz =	percent of S					
rz_1 =	0.5	Fraction %				
rz_2 =	1	Fraction %				
K_{NH} (rz_1) =	0.0829					
K_{NH} (rz_2) =	0.41074					
				rz_1	rz_2	
$K_T = K_{NH}((0.4103)$ at				0.0340	0.1685	
$K_T = K_{NH}((1.048)(T-20$				0.0519	0.2570	

Determine SF wetland area for ammonia removal.

K_T =		0.0519	d^{-1}		
rz_1 =	A_s =	687310	m^2	169.8	acres
HRT =	t =	26.7	d		
K_T =		0.2570	d^{-1}		
rz_2 =	A_s =	138695	m^2	34.3	acres
HRT =	t =	5.4	d		
Safety Factor =		25.0	%		
rz_1 As + Safety Fact		859137.9	m^2		
rz_1 HRT + Safety Fac		33.4	d		
rz_2 As + Safety Fact		173368.2	m^2		
rz_2 HRT + Safety Fac		6.7	d		

Determine the effluent nitrate.

K_{20} for denitrification		1	d^{-1}		
$K_T = K_{20}(1.15)(T-20)$					
K_T for denitrification		0.247	d^{-1}		
rz_1	C_e =	0.00	mg/L		

rz_2	C_e =	2.83	mg/L		
Determine SF wetland effluent TN.					
rz_1	TN =	5.00	mg/L	If <= C_e, OK	
rz_2	TN =	7.83	mg/L	If <= C_e, OK	

If greater than specified C_e mg/L, try anotheriteration with C_e smaller and size for ammonia removal.

Summary:								
	FWS wetland:							
		Total area =	106508	m^2	1146443	ft^2	26.32	ac
		HRT =	12.7	days	12.7	days		
	Average depth		0.6	m	2.0	ft		
	Effluent Tot N		5.7	mg/L				
	SF wetland:							
		Total area for rz_1 =	859138	m^2	9247674	ft^2		
		HRT for rz_1 =	33.4	days	33.4	days		
		Total area for rz_2 =	173368	m^2	1866118	ft^2	42.84	acres
		HRT for rz_2 =	6.7	days	6.7	days		
		Average water depth =	0.46	m	1.51	ft		
	Effluent Tot N		5.00	mg/L				
	Effluent Tot N		7.83	mg/L				

MUST CHANGE PRETREATMENT SYSTEM IF NOT A FACULTATIVE LAGOON

Nitrogen Removal in a Specified FWS Wetland Area for Various Months of the Year.

Surface area and HRT should be selected from values for N removal or phosphorus removal. N or P removal will control size of wetland

Surface Area FWS =		106508	m^2	HRT in FWS		12.7	d	
				HRT in Pon		119	d	
				Nitrogen C		45	mg/L	
				pH pond ef		8		
				FWS K_{20} =		0.2187	d^{-1}	
				FWS Theta		1.048		

			Pond Eff. TN	FWS	FWS	FWS	Fraction of	Un-Ionized NH_3
Month	Air Temp.	Pretreatment	C_o for FWS	Temp.	TKN K_T	TKN Conc.	Nitrogen as	in Effluent
	^{0}C	Water Temp.	Wetland	°C	d^{-1}	mg/L	Un-ionized NH_3	mg/L
			mg/L					
January	3.9	6	20.41	6	0.1134	4.85	0.0133	0.065
February	5.6	7	19.22	7	0.1189	4.26	0.0144	0.061
March	7.5	9	17.58	9	0.1306	3.37	0.0169	0.057
April	10.1	12	16.26	12	0.1503	2.42	0.0213	0.052
May	13.1	15	15.69	15	0.1730	1.75	0.0266	0.047
June	15.8	17	15.57	17	0.1900	1.40	0.0308	0.043
July	18.2	20	15.67	20	0.2187	0.98	0.0382	0.038
August	18.1	20	15.67	20	0.2187	0.98	0.0382	0.038
September	15.6	17	15.57	17	0.1900	1.40	0.0308	0.043
October	11.4	13	16.01	13	0.1575	2.18	0.0229	0.050
November	7.2	9	17.58	9	0.1306	3.37	0.0169	0.057
December	4.7	7	19.22	7	0.1189	4.26	0.0144	0.061
Mean Value		12.67	17.0	12.67		2.60		0.051

Nitrogen Removal Calculated with Kadlec and Knight Formula

Presented in "Treatment Wetlands" by Robert H. Kadlec and Robert L. Knight, CRC Lewis Publishers, Boca Raton, Florida, 1996.

$$A = \frac{Q \ln\left[\dfrac{C_{TN,i} - C_{TN}*}{C_{TN,0}Z - C_{TN}*}\right]}{k_{TN}}$$

See Table 13-12 for Limits and Reductions for Nitrogen Species in Wetlands. Same model applies for all species.

Insert Design Parameters in Shaded Fields

k_{20} = Reaction Rate	22	m/yr
Theta = Temperatur	1.05	

$C_{N,i}$ = Influent N Spe	20	mg/L
$C_{N,0}$ = Eff. N Species	5	mg/L
C^*_N = Background N	1.5	mg/L
k_T = Reaction rate at	13.51	m/yr
Temperature of Wat	10	deg. Celsius
Q = Design Flow Rat	3785	m^3/d
Z = Safety Factor =	0.625	Varies for species of nitrogen, see table below for species of interest.

AREA REQUIRED =	248794	m^2	61.48	Acres

Insert Values in Shaded Fields for Following Annual Performance Expectations

Design Flow Rate =	3785	m^3/d	1.000	MGD
Area of Wetland =	248794	m^2	61.48	acres
Inf. N Conc. (Eff. fro	20	mg/L		
K_{20} =	22	m/year		
K_T =	13.51			
Design Water Temp	10	deg. C		
Background N Conc	1.5	mg/l		
Depth =	0.6	m		
Z =	0.625			
HRT in Pond System	119	d		
Nitrogen Co in Pond Sys. =	45	mg/L		
pH pond effluent =	8			

Month	Average Precip. in/month	80 % of Avg. Pan Evapor. in/month	Total Flow of Waste m^3/d	Rainfall + WASTE m^3/d	Evaporation Flow Out m^3/d	Net Flow Entering Wetland m^3/d	HRT Wetland d	Average Air Temp. ^0C	Pretreat. Water T ^0C	Conc. of Nitrogen Into Wetland mg/L	Diluted Conc. of Nitrogen in Wetland mg/L	K_T m/year	Eff. - Background Concentration of Nitrogen $C_{N0}Z-C^*_N$ mg/L	Effluent Total Nitrogen mg/L
January	4.4	0	15142	16207.9	0.00	16207.9	9.21	3.9	6	20.41	19.1	11.11	11.01	20.02
February	3.2	0	15142	15917.2	0.00	15917.2	9.38	5.6	7	19.22	18.3	11.67	10.18	18.69
March	3	0	15142	15868.7	0.00	15868.7	9.41	7.5	9	17.58	16.8	12.86	8.79	16.47
April	1.3	0.216	15142	15456.9	45.50	15411.4	9.69	10.1	12	16.26	16.0	14.89	7.49	14.39
May	0.3	3.336	15142	15214.7	702.72	14512.0	10.29	13.1	15	15.69	16.4	17.24	6.62	12.99
June	0.1	3.984	15142	15166.2	839.22	14327.0	10.42	15.8	17	15.57	16.5	19.00	6.06	12.09
July	0	4.472	15142	15142.0	942.02	14200.0	10.51	18.2	20	15.67	16.7	22.00	5.29	10.86
August	0	3.824	15142	15142.0	805.52	14336.5	10.41	18.1	20	15.67	16.6	22.00	5.29	10.86
September	0.2	2.368	15142	15190.4	498.81	14691.6	10.16	15.6	17	15.57	16.1	19.00	6.03	12.04
October	1	1.224	15142	15384.2	257.83	15126.4	9.87	11.4	13	16.01	16.0	15.63	7.18	13.89

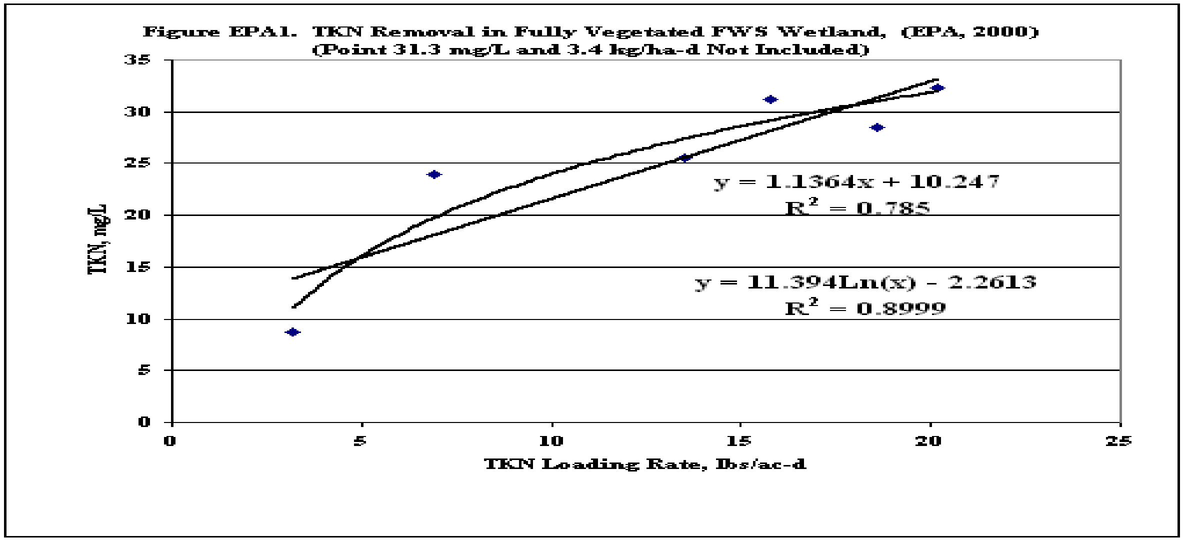
November	2.4	0	15142	15723.4	0.00	15723.4	9.49	7.2	9	17.58	16.9	12.86	8.84	16.54
December	3.5	0	15142	15989.9	0.00	15989.9	9.34	4.7	7	19.22	18.2	11.67	10.15	18.65
Mean Value	1.62	1.619	15142.0	15534	340.97	15192.7	9.83	10.93	12.67	17.0	16.9			14.79
Total	19.40	19.424	181704	186404	4091.63	182311.9								

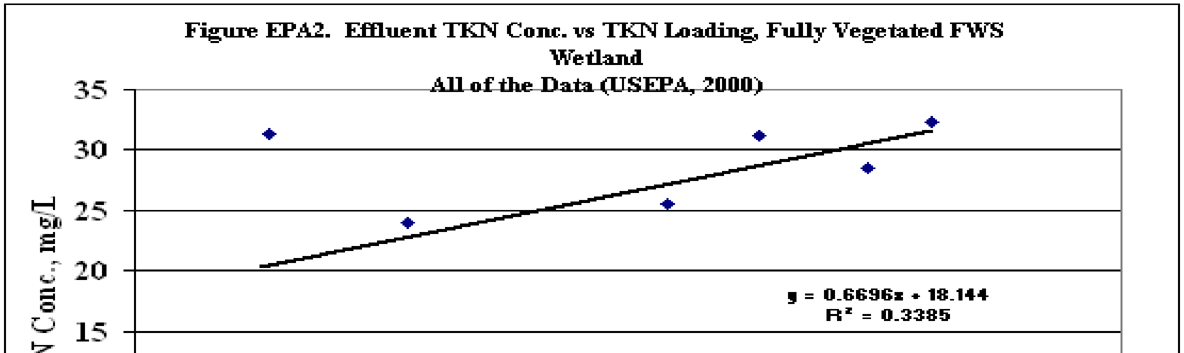
Table 13-12 Limits and Reductions for Nitrogen Species in Treatment Wetlands

		Organic N	Ammonium N	Nitrate N	Total Nitrogen
Surface Flow	Reductions				
	Rate constant = k_{20} =	17 m/yr	18 m/yr	35 m/yr	22 m/yr
30 cm deep	Theta (θ) =	1.05	1.04	1.09	1.05
	Background = C^* =	1.5 mg/L	0 mg/L	0 mg/L	1.5 mg/L
N loading @	90% to C^* in τ =	15 d	14 d	7 d	11 d
q = 5.0 cm/d	90% to C^* at q =	2.0 cm/d	2.1 cm/d	4.2 cm/d	2.6 cm/d
& 10 mg/L = 0.50 g N/m^2/d					
	Limits				
N loading @					
τ = 7 days	Carbon supply limit =			5 g N/m^3/d	
& 10 mg/L = 0.43 g N/m^2/d	Oxygen supply limit =		0.8 g N/m^2/d		
	Burial and volatilization =				0.1 g N/m^2/d
	Temporary plant uptake =		0.3 g N/m^2/d		0.3 g N/m^2/d
Subsurface flow	Reductions				
	Rate constant = k_{20} =	35 m/yr	34 m/yr	50 m/yr	27 m/yr
60 cm deep	Theta (θ) =	1.05	1.04	1.09	1.05
0.40 porosity	Background =	1.5 mg/L	0 mg/L	0 mg/L	1.5 mg/L
N loading @	90% reduction in τ =	6 d	6 d	4 d	7 d
q = 5.0 cm/d	90% reduction at q =	4.2 cm/d	4.0 cm/d	5.9 cm/d	3.2 cm/d

USEPA Nitrogen Removal

Presented in "Treatment Wetlands" by Robert H. Kadlec and
Robert L. Knight, CRC Lewis Publishers, Boca Raton, Florida, 1996.





Nitrogen removal in FWS constructed wetlands as described in the USEPA Design Manual (2000) is basicly limited to TKN removal. With lightly loaded (<5 kg of TKN/ha-d) fully vegetated wetlands, the manual predicts an effluent TKN of 10 mg/L or less. In lightly loaded FWS wetlands with significant open water, the effluent TKN concentration can be less than 5 mg/L.

Using the linear fit of the data in the Figure EPA 1 with an intercept of 10.2 mg/L, one can predict the performance of a fully vegetated FWS wetland.

$$\boxed{Effluent\,TKN\ Concentration, mg/L = 1.1364\left(Loading Rate, kg/ha-d\right) + 10.247}$$

Influent TKN Concen	**20mg/L**
Surface Area of FWS	**176565m^2**
Design Flow Rate =	**3785m^3/d**
Loading Rate =	**4.29kg/ha-d**
Effluent TKN Concen	**15.12mg/L**

Using the semi-ln fit of the data in Figure EPA1, the effluent TKN can be estimated.

$$\boxed{Effluent\,TKN\ Concentration, mg/L = 11.394LN\left(Loading\ Rate, kg/ha-d\right) - 2.2613}$$

Effluent TKN Concen **14.32mg/L**

Neither the linear nor the LN prediction equations support the EPA contention that at loading rates less than 5 kg/ha-d one can

expect a TKN concentration of 10 mg/L.

Chapter 5. Conclusions

1. Constructed wetlands coupled with lagoons are economical and energy efficient ways to treat wastewaters where land is available at competitive prices.
2. Careful consideration must be given to the biological and physical design of pretreatment processes and wetland processes.
3. Selection of the sizing procedure to be used is no more significant than the physical design features, i.e., hydraulics, overflow structures, provision of open water areas for nitrification, control of vegetation and aquatic animals.
4. Selection of the proper design parameters for the environmental conditions at the construction site is critical.
5. Attention to operational details is of great importance. There is no treatment process free of the need for proper operation and maintenance.
6. The benefits of wetlands wildlife habitat, erosion control, recreational aspects such as birding, walking and viewing nature must be considered when assessing the economics of constructed wetlands.

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